Influence of the positive ion thermal motion in the radial motion to orbital motion to cylindrical Langmuir probes in low pressure plasmas Part I: Ar^+

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The influence of the positive ion temperature to the electron temperature ratio, β, in the trajectory described by the positive ions when falling toward a negatively biased cylindrical probe is studied in a low pressure, low temperature Argon plasma. Several criteria had been applied to discriminate whether the ion movement falling toward the probe is described by using the Orbital Motion Limited theory or the radial motion theory. Although in all our Argon plasma conditions, the criteria indicate that the positive ion current collected by the probe is appropriately described by the radial motion theory, it has been pointed out that as β increases, the criteria indicate that the description tend to approach to the orbital motion theory. This can be explained since for the higher β values, the positive ion thermal velocity increases, so the azimuthal thermal velocity component can reach a large enough value that allow the ions to orbit when fall towards the probe, since for our plasma conditions, ions do not collide in the sheath.

1. Introduction

Knowledge about the trajectory of the ions falling toward a Langmuir probe is extremely important not only in plasma diagnosis, but also in material technological processes involving plasma wall/substrate interactions such as Plasma Assisted Chemical Vapor Deposition (PACVD), Ion Implantation, Etching, Surface Coating, Thin Films, Nanotechnology, etc., since the probe plays a role similar to the wall/substrate.

This work study the results obtained in the application of several criteria to discriminate the trajectory described by the Ar^+ ions when fall toward the probe in a low pressure, low temperature Argon plasma as a function of the parameter $\beta=T_i/T_e$, T_i, being the positive ion temperature, and T_e the electron one. All the criteria are based on the study of the ion saturation zone of the experimental current-voltage characteristic curve of a cylindrical Langmuir probe immersed in the plasma, $V_p \ll V_{plasma}$ (V_p being the biasing probe potential and V_{plasma} the plasma space potential). There are two well known limiting theories describing the ion current collected by the probe: on the one hand, the Orbital Motion Limited (OML) theory proposed by Mott-Smith and Langmuir in the 1920s [1]. This theory was extended by Bernstein and Rabinowitz for ions having a fixed but uniform total energy [2] and by Laframboise for ions following a Maxwellian distribution function [3]. On the other hand, the radial motion theory proposed by Allen, Boyd and Reynolds [4] for spherical probes and generalized by Chen for the case of cylindrical ones [5], which is usually referred to as the ABR theory. The ABR theory is valid for cold ions, β=0, and has been extended by the authors to include the influence of the positive ion thermal motion, $\beta \neq 0$ [6]. So, the existence of both theories implies a paradox in the analysis of positive ion saturation zone a Langmuir probe current-voltage characteristic, since it is unknown a priori which of both theories is applicable before it is applied [7].

Therefore, ion current collected by cylindrical Langmuir probes has been experimentally studied by several authors, concluding that usually is the radial theory who describes adequately their experimental results [8-12]. This result can be justified for plasma conditions corresponding to β values close to zero, considering that, on their way to the probe, the positive ions lose their translation kinetic energy when colliding with other particles present in the plasma, mainly neutrals [8, 10-13]. So, after the last collision, they fall towards the probe following a radial trajectory, as described by the ABR theory. Nevertheless, when the influence of the positive ion thermal motion is considered, $\beta\neq0$, after the last collision, the thermal velocity of the ions must be taken into account, since for large β values, its azimuthal component could be large enough, to allow them to orbit in their falling towards the probe. This fact justifies this work.

2. Results and conclusions

This section is devoted to the presentation and discussion of the applied criteria and the results obtained.

The experimental device used by the authors to obtain these measurements is widely developed in Refs.10, and 11.

The differences among the criteria are based on several questions like the number of points of the current-voltage probe characteristic curve used, the possibility of plot the evolution of the criterion result versus the β parameter, or the influence of the experimental noise in the result of the criterion, since the signal to noise ratio is higher in the ion saturation zone than in other zones of the current-voltage characteristic curve. In this way, since 153 current-voltage probe characteristic curves corresponding to the different plasma conditions have been measured, we have selected one current-voltage probe characteristic. This will be our reference case. The experimental conditions for the reference case are: P=21.4 Pa, I_d=1.8 mA, and β=0.11. Nevertheless, for the rest of the plasma conditions, the results are similar to the one obtained for this reference case.

These criteria are:

a) The proximity in the Sonin plot of the point, obtained from the electron density and temperature determined by using classical experimental diagnostic methods [10, 11 and 14], to the curves corresponding to the ABR or OML motion theories.

The Sonin plot is a useful representation of the positive ion current collected by the probe. For cylindrical and spherical probes, the Sonin plot is the representation of the dimensionless ion current

$$I'(x_p, y_p, \beta) = \frac{I_+(x_p, y_p, \beta)}{e r_p n_+}\sqrt{\frac{m_+}{2\pi k_B T_e}}, \qquad (1)$$

versus

$$I'(x_p, y_p, \beta)\cdot x_p^2 = \frac{I_+(x_p, y_p, \beta) e r_p}{\varepsilon_0}\sqrt{\frac{m_+}{2\pi k_B^3 T_e^3}}. \qquad (2)$$

m_+ being the positive ion mass, e the elementary charge, k_B the Boltzmann constant, λ_D the Debye length, ε_0 the vacuum dielectric permittivity, r_p is the probe radius, x_p the dimensionless probe radius ($x_p=r_p/\lambda_D$), y_p the dimensionless probe biasing potential ($y_p=-eV_p/k_BT_e$), I_+ the positive ion current collected by the probe per unit length when the probe is biased at V_p potential, referred to the plasma potential, and n_e the electron density of the plasma. We have chosen in this work y_p=25. So, the experimental values measured for the I_+, x_p, y_p, β, n_e, and T_e values, measured from the experimental current-voltage characteristic curve and by direct integration of the Electron Energy Distribution Function (EEDF) provide a point in the Sonin plot.

The criterion consist on the study of the approaching of this point to the theoretical curves plotted in the Sonin plot corresponding to the ion current collected by the probe obtained from the OML and ABR theories. Figure 1 illustrated a Sonin plot including the theoretical OML and ABR curves for three interval of the β parameter. Moreover, 153 points, obtained from current-voltage characteristics corresponding to the same number of different plasma conditions, has been plotted. As can be seen, according to this criterion, the ions fall towards the probe following the ABR theory for all the studied plasma conditions.

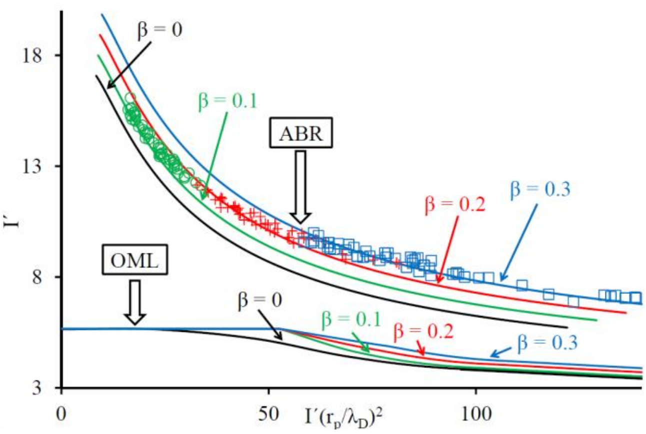

Figure 1. Sonin plot including the experimental data (symbols) and theoretical curves (solid lines) for Argon plasmas, y_p=25. Circles mean $0.08\leq\beta\leq0.15$, crosses mean $0.16\leq\beta\leq0.25$, and squares mean $0.26\leq\beta\leq0.34$.

The favourable aspect of this criterion is that it let us a plasma diagnosis technique by using the ion saturation zone of the current-voltage characteristic curve. Nevertheless, the inconvenience is that it uses only one experimental point of the current to voltage characteristic.

b) The second criterion is the comparison between the experimental current-voltage characteristic curve of the reference case, for $V_p<V_{plasma}$ values, and the theoretical one obtained from the ABR theory considering the influence of the positive ion thermal motion. It has been obtained by adding to the theoretical I_+-V curve, the theoretical contribution due to the electrons $I_-(V_p\leq V_{plasma})=A_p e n_e(k_B T_e/2\pi m_e)^{1/2}$ (A_p being the probe surface), since our measured EEDF approaches to a Maxwellian one. Figure 2 illustrates such a comparison. As can be seen in figure 2, there is a very good agreement between them. So we can conclude that, under the 153 studied plasma conditions, the ions fall toward the probe following a radial trajectory.

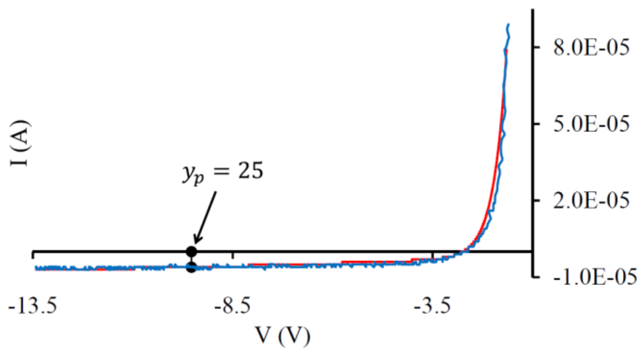

Figure 2. Theoretical (red line) and experimental (blue line) *I-V* characteristic.

c) The third criterion is the study of the linear approaching of the experimental plot I_+^2 versus V which must be accomplished if the OML motion theory is fulfilled. In this way, the I_+^2 versus V experimental data in the interval $y_p\pm3k_BT_e$, of the current to voltage characteristic measured for all the studied plasma conditions, have been fitted to a straight line by using the least squared method obtaining a linear correlation coefficient always lower than 0.5, for the intervals always containing more than 100 data. Moreover, there is a difference higher than 60% between the n_e values obtained by direct integration of the EEDF and the one obtained from the slope of the I_+^2 versus V fit, for all the 153 studied cases. So we can conclude that, under our discharge conditions, the ions do not fall toward the probe following an orbital trajectory.

As in the a) criterion, the favourable aspect of this one is that it uses a wide interval of the current-voltage characteristic curve, while the inconvenience is that it not let to study its evolution as a function the β parameter.

d) The Allen-Annaratone criterion [8] shows that the OML theory will not be valid if

$$\lambda < r_p\left(-eV_p/k_BT_i\right)^{1/2} \quad (3)$$

in a collision-free plasma of infinite extent.

The right term of the inequality, the effective radius of the probe for capture when the energy E_0 of the ions at large distances from the probe is a small quantity compared with $|eV_p|$).

This condition is quite restrictive since $\lambda/r_p<28.79[T_e(eV)]^{1/2}$ for Argon plasma, T_i=350 K and eV_p/k_BT_e=-25.

We have considered that the value of the mean free path for ion-atom collisions is 0.74 mm [15-17].

As shown in Figure 3, when β increases the behavior of ions falling to the probe is not orbital since the experimental measurements do not cross the value limit 0.74 mm (red line).

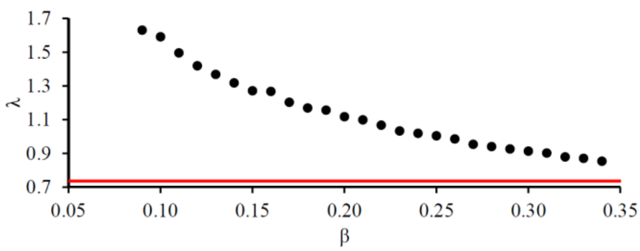

Figure 3. Allen-Annaratone criterion: Evolution of experimental measurements with the β parameter.

e) The Pilling and Carnegie criterion [7] is a consequence of the previous one. These authors proposed the study of the plot of d(log$_{10}$ V)/d(log$_{10}$ I) versus V_p. Obviously, for V_p values very distant from the plasma potential, V_{plasma}, the curve will tend to 2 if charged particles fall towards the probe accomplishing the OML theory.

Figure 4 shows the d($\log_{10} V$)/d($\log_{10} I$) versus V_p plots for the ions saturation, $V_p \ll V_{plasma}$. For each case plotted in figure 4 we have taken an interval $y_p \pm 2k_B T_e$. As can be seen, the curve do not tends the value 2. So we can conclude that under the studied discharge conditions, the ions do not fall toward the probe following an orbital trajectory.

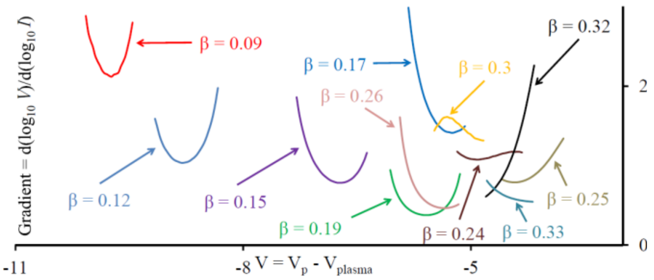

Figure 4. Pilling and Carnegie criterion: Evolution of experimental measurements with the β parameter.

Summarizing, both d) and e) criterion discriminate whether the ions fall towards the probe following an orbital trajectory.

As conclusions, our measurements are accurate enough to discriminate and explain the experimental plasma conditions for each theory to be appropriate in each case. So, we believe that this work substantially advances the knowledge about the plasma wall interaction and solves a critical outstanding problem such as how the ions move in the surroundings of a cylindrical surface immersed in the plasma. Therefore, it will cause new studies related to Plasma Physics and Material Science both in the theoretical aspect and in the experimental one.

3. Acknowledgments

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